Transcription factor ISL1 is essential for pacemaker development and function

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The sinoatrial node (SAN) maintains a rhythmic heartbeat; therefore, a better understanding of factors that drive SAN development and function is crucial to generation of potential therapies, such as biological pacemakers, for sinus arrhythmias. Here, we determined that the LIM homeodomain transcription factor ISL1 plays a key role in survival, proliferation, and function of pacemaker cells throughout development. Analysis of several *Isl1* mutant mouse lines, including animals harboring an SAN-specific *Isl1* deletion, revealed that ISL1 within SAN is a requirement for early embryonic viability. RNA-sequencing (RNA-seq) analyses of FACS-purified cells from ISL1-deficient SANs revealed that a number of genes critical for SAN function, including those encoding transcription factors and ion channels, were downstream of ISL1. Chromatin immunoprecipitation assays performed with anti-ISL1 antibodies and chromatin extracts from FACS-purified SAN cells demonstrated that ISL1 directly binds genomic regions within several genes required for normal pacemaker function, including subunits of the L-type calcium channel, *Ank2*, and *Tbx3*. Other genes implicated in abnormal heart rhythm in humans were also direct ISL1 targets. Together, our results demonstrate that ISL1 regulates approximately one-third of SAN-specific genes, indicate that a combination of ISL1 and other SAN transcription factors could be utilized to generate pacemaker cells, and suggest ISL1 mutations may underlie sick sinus syndrome.

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The sinoatrial node (SAN) maintains a rhythmic heartbeat; therefore, a better understanding of factors that drive SAN development and function is crucial to generation of potential therapies, such as biological pacemakers, for sinus arrhythmias. Here, we determined that the LIM homeodomain transcription factor ISL1 plays a key role in survival, proliferation, and function of pacemaker cells throughout development. Analysis of several Isl1 mutant mouse lines, including animals harboring an SAN-specific Isl1 deletion, revealed that ISL1 within SAN is a requirement for early embryonic viability. RNA-seq analyses of FACS-purified SANs revealed that a number of genes critical for SAN function, including those encoding transcription factors and ion channels, were downstream of ISL1.

Introduction

Rhythmic contraction of the heart is controlled by electrical impulses generated by pacemaker cells of the sinoatrial node (SAN). Abnormalities in SAN development lead to cardiac arrhythmia and sudden death (1). Sick sinus syndrome is a common age-related SAN dysfunction that ultimately requires implantation of a permanent pacemaker (2, 3). Despite its marked clinical relevance, genes and signaling pathways required for progressive development of effective therapies for sinus arrhythmias, including the possibility of biological pacemakers (4).

Pacemaker activity of SAN cells is due to slow diastolic depolarization generated by several ion channels, including calcium channels and hyperpolarization-activated cyclic nucleotide-gated potassium/sodium channels (HCN channels), which are modulated by autonomic neurons (5, 6). Molecular mechanisms underlying automaticity of the SAN are subject of intensive study, and a complex coupled-clock system has been proposed: the voltage clock generated by HCN channels (the current referred to as If, the “funny” current); and the calcium clock generated by rhythmic Ca2+ release from sarcoplasmic reticulum. Both mechanisms act independently and synergistically to initiate the heartbeat (5, 7, 8).

Of 4 HCN channels, HCN4 is the most highly expressed in the SAN. During development, HCN4 expression is initiated in the cardiac crescent and is progressively confined to and later maintained in the SAN during later development and in the adult (9–11). Mutations in the human HCN4 gene lead to sinus bradycardia and have been associated with inherited sick sinus syndrome, long QT syndrome with bradycardia, and ventricular tachycardia (12–17). Mouse embryos that are null for Hcn4 exhibit long pauses in heartbeat and die around E10.5, demonstrating a critical requirement for Hcn4 in early pacemaker function of the heart (11). However, mice with Hcn4 deleted during later developmental stages and postnatal life survive, exhibiting normal basal heart rate with periodic long pauses. This observation, together with other in vitro physiological studies, suggest a role for If in stabilizing the pacemaker rhythm in later-stage hearts (18, 19).

Calcium release and cycling via the ryanodine receptor (RyR2), the sarcoplasmic reticulum calcium ATPase (SERCA2), the sodium calcium exchanger (NCX), and associated regulatory proteins play an essential role in pacemaker automaticity (20–23). Deletion of Ryr2 or Ncx1 leads to early embryonic lethality and substantial impairment in pacemaker function (22, 24). Phosphorylation of...
ISL1 is a LIM homeodomain transcriptional factor that marks undifferentiated cardiac progenitors of the second heart field and is required for these progenitors to contribute to the heart (52). ISL1-expressing progenitors have the potential to develop into multiple cell types within the heart, including cardiomyocytes, smooth muscle cells, pacemaker cells, and endothelial cells (52–54). Recent studies have shown that ISL1 expression is maintained in the SAN (54–56). In zebrafish, Isl1 mutation results in bradycardia and irregular heartbeat with frequent pauses (57, 58). In Shox2-deficient mice, expression of ISL1 is diminished in SAN. ChIP-PCR revealed that SHOX2 binds to and regulates expression of an Isl1 enhancer. Overexpression of ISL1 can rescue the bradycardia phenotype in Shox2-deficient zebrafish (59). Due to early lethality and loss of cardiac cells derived from ISL1 progenitors in Isl1-null mice, a specific role for ISL1 in the SAN remains unknown. Recent transcriptome studies demonstrated changes in gene expression in response to Isl1 ablation in the SAN (60). However, no studies have been performed to address phenotypic or physiological consequences of Isl1 ablation. Furthermore, direct targets of ISL1 action in SAN cells remain unexplored.

In this study, we generated several Isl1 mutant mouse lines with reduced ISL1 expression, with Isl1 ablation specifically in differentiated cardiomyocytes, or with Isl1 ablation specifically in SAN cells. Our studies uncover a cell-autonomous requirement for ISL1 within the SAN in regulating proliferation, survival, and pacemaker function. Furthermore, we have performed RNA-sequencing (RNA-seq) studies of Isl1 mutant and control purified SAN cells, intersecting these data with genome-wide chromatin immunoprecipitation studies utilizing antibodies to ISL1 on chromatin from purified SAN cells to gain insight into mechanisms by which ISL1 regulates SAN formation and function.

Results

ISL1 is expressed in cardiac pacemaker cells of the SAN. To investigate the role of ISL1 in SAN formation and function, we first analyzed ISL1 expression during SAN development and performed coimmunostaining utilizing antibodies for markers of SAN and surrounding atrial myocardium. HCN4 is a pacemaker channel expressed within the heart during early developmental stages, with its expression progressively being confined to and specifically marking the SAN (9, 10, 61, 62). At E9.5, ISL1 was expressed in myocardium of the SV, the primitive pacemaker region of early-stage embryos, where it was strongly coexpressed with HCN4 (Figure 1A). At E10.5, ISL1 and HCN4 were coexpressed in the head (Figure 1B) and tail (Figure 1C) of the SAN, venous valves (vv), and atrial myocardium surrounding the dorsal mesocardium (DM) (Figure 1, A and B). During later developmental stages and early postnatal life, ISL1 was expressed in a majority of SAN cells marked by HCN4 (Figure 1, D, F, and H). ISL1 expression in the SAN gradually decreased with age. The percentage of ISL1-expressing cells relative to the total number of HCN4+ pacemaker cells decreased markedly 2 weeks after birth and continued to decrease with age (Figure 1, I and H). Cx40 was expressed in atrial myocardium complementary to ISL1 expression in the SAN (Figure 1, E and G). These observations suggested a role for ISL1 in SAN development and function.
Reduced Isl1 expression in Isl1 compound mutant embryo leads to sinus arrhythmia and loss of SAN cells. To better visualize ISL1 expression during development and investigate the role of ISL1 in SAN formation and function, we generated Isl1 compound mutants with a less severe cardiac phenotype than that of Isl1 global null mutants (52), allowing for later survival. Isl1 compound mutant mice were generated by crossing an Isl1 nuclear LacZ knockin/knockout mouse line (Isl1nLacZ) (54, 63) and an Isl1 hypomorphic mouse line (floxed Isl1 allele with neomycin, Isl1flo:Neo), in which the presence of the neomycin cassette interferes with Isl1 expression (64). The Isl1 compound mutant (Isl1nLacZflo:Neo) exhibits further reduction in Isl1 expression and is embryonic lethal around E11.5 (63).

X-gal staining of tissue sections from control Isl1nLacZ mice revealed that Isl1-nLacZ expression recapitulated endogenous Isl1 expression, as previously published (52). Consistent with data shown in Figure 1, Isl1-nLacZ was expressed in DM, the SAN, and surrounding atrial myocardium at E9.5 (Figure 2, A and C). At E11.5, Isl1-nLacZ expression was observed in the SAN (Figure 2, G and I). However, in Isl1 compound mutants at E9.5 and E11.5, the number of cells expressing Isl1-nLacZ in SV myocardium, the SAN, and DM was substantially reduced (Figure 2, B, D, H, and J). Immunostaining with ISL1 and HCN4 antibodies revealed markedly reduced expression of ISL1 and HCN4 in the SV of Isl1 compound mutant embryos at E9.5 compared with littermate controls (Figure 2, E and F).

These observations suggested that ISL1 may be required for proliferation and/or survival of SAN cells, SV cardiomyocytes, and/or cardiac progenitors of the posterior heart field. Therefore, we analyzed proliferation by BrdU labeling and cell death by TUNEL staining. The SV at E9.5 functions as a pacemaker region. We observed a significant reduction in the number of BrdU-labeled cells in SV myocardium (Figure 2, K–M) and a significant increase in cell death in the right horn of the SV at E9.5 (Figure 2, N–P).

To test whether pacemaker function was compromised in Isl1 compound mutants, we performed echocardiography to examine heart rate from E9.5–E11.5. Individual embryos were mapped in utero and analyzed by echocardiography to evaluate heart rate. The heart rate of Isl1 compound mutant embryos was significantly slower at E9.5 and further decreased at E11.5 (Figure 2Q). We also observed periodic heart-rate variability with long pauses, the frequency and duration of which were increased with embryonic age. Some embryos with long pauses in heartbeat died during the course of the examination, strongly suggesting that Isl1 mutant embryos died of cardiac arrhythmia.

Reduced Isl1 expression in Isl1 compound mutant embryo results in reduced expression of genes critical to SAN function. HCN4, SHOX2, and TBX3 are critical factors for SAN development and function. In situ hybridization revealed that Hcn4, Shox2, and Tbx3 were expressed in SV of control littermates at E9.5 (Figure 3, A, C, E, G, I, and K), but their expression was markedly reduced in SV of Isl1 compound mutant embryos (Figure 3, B, D, F, H, J, and L). Cx40 and Nkx2.5 were expressed in myocardium of control embryos but not in the SAN (Figure 3, M, O, Q, and S). In contrast to ectopic expression previously observed in Shox2 and Tbx3 mutants, we did not observe ectopic expression of Cx40 or Nkx2.5 in Isl1 compound mutants (Figure 3, N, P, R, and T). Together, these observations suggested a general loss of cells in this region in the compound mutant.

Specific ablation of Isl1 in differentiated cardiomyocytes. Reduced ISL1 expression in Isl1 compound mutant mice might affect both differentiated SAN pacemaker cells and progenitors of the second heart field that contribute to SV myocardium and the SAN. To investigate a potential direct role for ISL1 in differentiated cardiomyocytes, we ablated Isl1 using cardiac Troponin T-Cre (cTnT-Cre) mice (65). Similar to phenotypes observed in Isl1 compound mutants, cTnT-Cre Isl1fl:Neo mutants died from E9.5–E11.5 and displayed severe bradycardia, increased heart-rate variability, and...
mice into Rosa-LacZ or Rosa-tdTomato indicator backgrounds to allow for Cre lineage tracing.

To determine temporal requirements for ISL1 in formation and function of the SAN, we ablated Isl1 specifically in pacemaker cells of the SAN using Hcn4-CreERT2 by giving tamoxifen at distinct times during development. At E9.5, the SV at the posterior pole of the heart functions as a primitive pacemaker. The first structurally discernable SAN is formed at E11.5, which becomes further matured and fully functional by E13.5 (31, 32). Therefore, we focused our study on these critical windows of SAN development. Tamoxifen was given at E9.5, and embryonic heart rate was examined daily by echocardiography. We found that, compared with control littermates, the heart rate of Hcn4-CreERT2 Isl1fl/fl mutants was significantly slower at E10.5. The heart rate of Hcn4-CreERT2 Isl1fl/fl mutants was further reduced at E11.5 with periodic long pauses, and a majority of these Hcn4-CreERT2 Isl1fl/fl mutants died around E11.5 (Figure 4A).

To examine the number and distribution of SAN cells in Hcn4-CreERT2 Isl1fl/fl mutants and somite-matched littermates, we performed lineage-tracing experiments in a Rosa-LacZ or Rosa-tdTomato reporter background. Tamoxifen was given at E9.5, and embryos were analyzed at E11.5 (48 hours after induc-

Figure 2. Bradycardia and loss of SAN cells in Isl1 compound mutants. ISL1-nLacZ was expressed in SV myocardium, including the SAN region (red arrow), and mesocardium at E9.5 (A and C) and E11.5 (G and I). Expression of ISL1 and HCN4 in the SV region of Isl1 compound mutant embryos was significantly reduced (E and F). Expression of ISL1 and the number of ISL1-expressing cells in the SV, SAN (red arrow), and DM was markedly reduced in Isl1 compound mutant embryos at E9.5 (B and D) and E11.5 (H and J). BrdU staining revealed significantly reduced proliferation of SV myocardium in Isl1 compound mutants at E9.5 (K–M). TUNEL labeling showed significantly increased cell death in the SV of Isl1 compound mutant embryos at E10.5 (N–P) (n = 4 per group. Scale bars as shown). Echocardiography revealed a significant reduction in the heart rate of Isl1 compound mutant embryos at E9.5 and E11.5 (Q). n = 15 per group; *P < 0.05, 2-tailed t test.
Furthermore, in Hcn4-CreERT2 Isl1fl/fl the SV of mutants was somewhat reduced (Figure 4, C and D). However, the number of Hcn4-CreERT2 lineage–labeled background (Figure 4, E–H).

bodies to HCN4 and TBX3 in an Hcn4-CreERT2 Rosa-tdT omato as revealed by coimmunofluorescence studies utilizing anti- HCN4 and TBX3 was markedly reduced in remaining SAN cells, changes in the number of X-gal + cells were observed in mutant, compound mutant embryos, expression of Cx40 and Nkx2-5 were mark-

EDLY reduced in atrial myocardium, but no expansion or ectopic expression of Cx40 or Nkx2-5 was observed in the SAN region (Figure 4, N–P). When tamoxifen was given at E11.5, Isl1 mutant embryos displayed a significantly slower heart rate when examined by echocardiography at 24 and 72 hours after induction (Figure 5A). In contrast to ablation of Isl1 at earlier stages, however, a majority of mutant embryos survived. When tamoxifen was given at E13.5, a significant reduction in heart rate was observed 48 hours after induction (Figure 5B). During these stages of development, the heart rate of control embryos increased gradually; however, the heart rate of Hcn4-CreERT2 Isl1fl/fl mutants did not increase and exhibited more variability (Figure 5B). Whole mount and section X-gal staining of E14.5 hearts (tamoxifen induced at E11.5) showed a slightly reduced intensity of X-gal+ cells in SAN of Isl1 mutants (Figure 5, D and F) when compared with SAN of littermate controls (Figure 5, C and E).

Quantitative analysis revealed a slight but significant decrease in the number of X-gal+ cells in the SAN of Isl1 mutants (3,635 ± 254 per SAN) compared with controls (4,441 ± 368 per SAN) (Figure 5G). Consistent with this, we observed a significant decrease in the number of proliferating cells (BrdU+) in Isl1 mutant SAN marked by Hcn4-CreERT2 Rosa-LacZ (Figure 5, H–J). However, in contrast to earlier stages, no significantly increased cell death was observed in the SAN of Hcn4-CreERT2 Isl1fl/fl mutants (not shown). At E14.5, Isl1 and HCN4 coimmunostaining revealed effective loss of ISL1 expression when tamoxifen was given at E11.5 (Figure 5, K and L). Furthermore, expression of HCN4 and TBX3 was markedly reduced in Isl1 mutant SAN marked by the Rosa-tdTomato reporter (Figure 5, M–P). Despite significant reduction in the expression of TBX3, no ectopic expression of NKKX2.5 was observed in Isl1 mutant SAN (not shown).

RNA-seq analyses reveal dysregulation of a number of genes important for SAN function in Hcn4-CreERT2 Isl1fl/fl mutants. To investi-
Figure 4. Bradycardia and loss of SAN cells following ablation of Isl1 in SAN during early developmental stages using Hcn4-CreERT2. Isl1 mutant (Hcn4-CreERT2 Isl1fl/fl) and control (Hcn4-CreERT2 Isl1+/+) embryos were given tamoxifen at E9.5. Embryos were analyzed 36 and 48 hours after induction. (A) Echocardiography revealed that the heart rate of Isl1 mutants was significantly reduced at E11 and was further reduced at E11.5 (n = 20 per group). (B-D) Whole-mount X-gal staining and quantitative analysis revealed a significantly reduced number of X-gal+ and Tomato+ cells in the SAN (red arrow) of Isl1 mutants relative to control littermates at E11.5 (n = 4. Scale bars as shown). (D-H) Immunostaining demonstrated significantly reduced expression of Hcn4 and TBX3 in the SAN of Isl1 mutants compared with controls marked by Tomato+ at E11.5. However, a slight but not significant reduction in the number of Hcn4 lineage–labeled cells in Isl1 mutant SAN region was observed when analyzed at E11 (D, I, and J). (K-M) TUNEL revealed increased cell death in Isl1 mutant SAN marked by Tomato. n = 4; *P < 0.05, 2-tailed t test. Scale bars as shown.

gate potential direct or indirect downstream targets of Isl1 that could account for observed phenotypes. RNA-seq analyses were performed on samples from Hcn4-CreERT2 Isl1fl/fl mutant and control SANs induced with tamoxifen at E10 and harvested at E12.5 (Figure 6). Results demonstrated that, of 12,441 genes expressed at significant levels in the SAN, transcripts for 3,690 (30%) of them were downregulated, and transcripts for 1,035 (8%) of them were upregulated in Isl1 mutants (fold-change Hcn4-CreERT2 Isl1fl/fl mutant vs. ctrl ≥ 1.5) (Figure 6, A and B, and Supplemental Table 1). Gene ontology (GO) and reactome pathway enrichment analysis demonstrated significantly affected categories in genes downregulated or upregulated in Isl1 mutants. For downregulated genes, extracellular matrix components, cell adhesion, and cell guidance categories were prominent. For upregulated genes, categories included potassium channel complex components and striated muscle contraction (Figure 6C, Supplemental Figure 3, and Supplemental Table 2). We examined significantly altered genes for those that might contribute to the observed Isl1 mutant SAN phenotypes, confirming alterations in their expression by quantitative PCR (qPCR) analyses (Figure 6, D and E, and Supplemental Table 3). These included ion channels and associated genes (Cacna1a, Cacna1d, Cacnb1, Hcn4, Kcnl1, and Ank2), genes involved in transcriptional regulation (Shox2, Tbx3, Ehmt2, Hdac7, Smyd, and Arid1b), cell cycle (Arid1b, Wdr62, Kras, and Mhc), and signaling pathways (Bmp4, Rgs4, Calcitonin receptor-like [Calcr], Klotho [Kl], Sema3c, and Sema3d), many of which play a role in heart development or are critical for SAN function (Figure 6D). Consistent with previous RNA-seq data (60), we observed significant upregulation of a number of atrial myocardial specific genes, including Nppa, Nppb, Gja1/Cx43, and Gja5/Cx40 (Figure 6E).

Isl1 directly regulates a number of genes required for normal pacemaker function in mice and human. To gain insight into direct downstream targets of Isl1 that could account for the observed SAN phenotype, we performed genome-wide ChIP-seq analyses on FACS-purified Hcn4-H2BGFP–expressing neonatal SAN cells (61). Analyses of these data revealed 1,483 ChIP-seq peaks for Isl1, with the majority of binding, 94.6%, occurring at intergenic or intronic sites (Figure 7A). The spatial distribution for Isl1 occupancy is consistent with other reports of cell type–specific binding patterns of transcription factors, localizing to transcription start site distal enhancer regions

\[ A \]

Heart rate

\[ B \]

E9.5–11.5

\[ C \]

TUNEL/Tom

\[ D \]

BrdU/Tom

\[ E \]

HCN4/Tom

\[ F \]

Hcn4-H2BGFP

\[ G \]

Tbx3/Tom

\[ H \]

BroU/Tom

\[ I \]

E9.5–11.5

\[ J \]

mut

\[ K \]

ctrl

\[ L \]

mut

\[ M \]

mut

\[ N \]

mut

\[ O \]

mut

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matrix disassembly, axon guidance, and cell proliferation — categories overall similar to those overrepresented in genes found to be downregulated by RNA-seq analyses. For direct targets of ISL1 upregulated in Hcn4-CreERT2 Isl1fl/fl mutants, overrepresented categories included regulation of sequence-specific DNA binding activity and transporter activity (Figure 7F, Supplemental Figure 4, and Supplemental Table 2). Examination of direct targets downregulated in Isl1 mutants revealed several genes known to be critical for SAN function, including Ank2 and Kl (refs. 69, 70, and Table 1). Although Tbx3 was one of the most highly downregulated genes, and Tbx3 mutation has been shown to result in bradycardia and heart-rate variability (34, 46) — phenotypes similar to those observed in Isl1 mutant SANs — analyses of our ChIP-seq data did not assign any ISL1 ChIP-seq peaks to the Tbx3 promoter, based on proximity to the nearest transcription start site. Because enhancers can regulate genes at long distances, we postulated that ISL1 might bind to a long-range enhancer to regulate expression of heart rates around E11.5. The foregoing demonstrated an indispensable role for ISL1 in cardiac pacemaking and embryonic viability at these early stages. Lineage tracing of Hcn4-CreERT2 cells revealed a reduced number of pacemaker cells at E11.5 when Isl1 ablation was induced at E9.5, which could be accounted for by increased cell death or ablation of Isl1 mutants induced at E11.5 or E13.5) resulted in similar bradycardia and heart-rate variability, and reduced proliferation in mutants relative to control littermates. Reduced ISL1 expression with only a slight loss of pacemaker cells. 

Discussion

ISL1 is required for proliferation, survival, and function of SAN cells at distinct stages throughout SAN development. Reduced ISL1 expression in Isl1 compound mutants, or ablation of Isl1 by tamoxifen injection at E9.5, resulted in severe bradycardia, increased heart-rate variability, and prolonged sinus pauses, with Isl1 mutant embryos dying in utero with severely slowed heart rates around E11.5. The foregoing demonstrated an indispensable role for ISL1 in cardiac pacemaking and embryonic viability at these early stages. Lineage tracing of Hcn4-CreERT2 cells revealed a reduced number of pacemaker cells at E11.5 when Isl1 ablation was induced at E9.5, which could be accounted for by increased cell death and reduced proliferation in mutants relative to control littermates. Marked reduction of TBX3 and HCN4 was also observed in remaining lineage-traced pacemaker cells in Hcn4-CreERT2 Isl1fl/fl mutants, suggesting that regulation of these genes is directly or indirectly downstream of ISL1 in SAN cells.

Ablation of Isl1 at later stages with Hcn4-CreERT2 (by administration of tamoxifen at E11.5 or E13.5) resulted in similar bradycardia, increased heart-rate variability, and reduced Hcn4, Tbx3, and Shox2 expression with only a slight loss of pacemaker cells. Cell loss was correlated with reduced rates of proliferation but no increased apoptosis. Hcn4-CreERT2 Isl1fl/fl mutants induced at these later stages were able to survive.
ISL1 is upstream of ion channels and transcription factors required for SAN function. To gain insight into genes downstream of ISL1 that might account for observed SAN phenotypes, we performed transcriptome analyses on RNA from FACS-purified SAN cells from Hcn4-CreERT2 Isl1flox/flox mutants and littermate controls that had tamoxifen induced at E10 and harvested at E12. Bioinformatics analyses of these data revealed decreased expression of a number of key ion channel and cardiac transcription factor genes in Hcn4-CreERT2 Isl1flox/flox mutant SAN.

SAN function is thought to be dependent on a 2-clock mechanism: the calcium clock and a voltage clock (5, 6). Decreased expression of mRNA encoding critical components of each of these clocks was observed in Isl1 mutant SAN cells, including mRNA for genes encoding subunits of the L-type calcium channel, Cacna1a, Cacna1b, Cacnb1, and Hcn4, a key component of the voltage clock. Germline ablation of Hcn4 results in severe bradycardia and early embryonic lethality, with embryos dying around E10–E11 (11). However, later ablation of Hcn4 utilizing an inducible Cre does not affect viability but results in sinus pauses and increased heart-rate variability (19). Mutations in the human Hcn4 gene also lead to sinus bradycardia and have been associated with inherited sick sinus syndrome (12–17).

Transcription factors that are critical for SAN function were significantly downregulated in Hcn4-CreERT2 Isl1flox/flox mutants, including Shox2 and Tbx3. Germline ablation of Shox2 results in SAN hypoplasia and bradycardia (49–51). Tbx3 is selectively expressed in the cardiac conduction system, and aberrations in Tbx3 are associated with human arrhythmias (74). Hypomorphic and conditional mutants of Tbx3 in mice exhibit sinus bradycardia and sinus pauses (46).

We also observed significant upregulation of transcripts from several genes characteristic of atrial phenotype, including Nppa, Nppb, Gja1/Cx43, and Gja5/Cx40 (44) in Hcn4-CreERT2 Isl1flox/flox mutant SANs. Interestingly, Tbx3 and Shox2 mutants also display upregulation of Gja5/Cx40 in the SAN (34, 36, 46, 49–51).

Decreased expression of a number of other genes associated with aberrant pacemaker function was also observed in Hcn4-CreERT2 Isl1flox/flox mutant SANs. These included Ank2, KI, Wdr62, and Calcr. Two families with highly penetrant and severe sinus node dysfunction have been mapped to the Ank2 locus, and mice heterozygous for Ank2 display severe sinus node dysfunction, including severe bradycardia and heart-rate variability (69), as observed in our Isl1 SAN mutants. ANK2 is required for normal membrane trafficking and organization of ion channels and transporters essential for SAN function. KI is selectively expressed in SAN within the heart, and ablation of KI results in an inability of the SAN to respond to stress (70). Human mutations in WDR62, required for mitotic spindle formation, result in a recessive syndrome of microcephaly, cerebellar hypoplasia, and congenital bradycardia with irregular heart rate (75). Human variants in Calcr, encoding the adrenomedullin receptor, have been associated with irregular heart rate (73). Mice with global knockout of Calcr die between E13.5–E14.5 and exhibit cardiac defects (76).

Both early- and later-stage ablations of Isl1 adversely affected proliferation of SAN cells. Expression of 2 widely utilized cell cycle genes, Kras and Myc, was significantly downregulated in SANs from Hcn4-CreERT2 Isl1flox/flox mutants. The potential role of these genes in SAN remains to be explored. The foregoing results suggest that aberrant regulation of a number of genes important for SAN phenotype and function contributes to the SAN phenotype of Hcn4-CreERT2 Isl1flox/flox mutants.

Genome-wide ChIP-seq studies of purified SAN cells reveal critical direct targets of ISL1 and suggest potential cofactor families for ISL1 action in SAN cells. To gain insight into mechanisms by which ISL1 regulates SAN phenotype and function, we performed ChIP-seq studies utilizing antibodies to ISL1 on purified SAN cells. Intersection of ChIP-seq and RNA-seq data demonstrated that several genes critical to SAN function in mouse and/or human were directly activated by ISL1 in SAN cells, including Ank2, KI, Tbx3, Calcr, and Flrt2 (46, 69, 70, 73, 74). Human variants in FLRT2 have been associated with irregular heart rate, although the potential role of FLRT2 in SAN function has not yet been validated in experimental models (73).

Bioinformatics analyses of DNA binding motifs enriched within ISL1 ChIP-seq peaks in SAN cells revealed enrichment for other homeodomain and FOX transcription factor binding sites, suggesting that members of these transcription factor families may cooperate with ISL1 to regulate expression of SAN genes. Notably, SHOX2 is another homeodomain transcription factor known to be important for SAN function (49–51, 59). FOX factors that may be important for SAN function remain to be identified.

Sick sinus syndrome accounts for the necessity of approximately half of the pacemaker implants within the United States (2, 3). Gene transfer and reprogramming of working cardiomyocytes or stem cells into pacemaker cells to generate a biological pacemaker represents a promising alternative therapy for sick sinus syndrome. Overexpression of HCN4 is sufficient to induce pacemaker function and has been successful in generation of a biological pacemaker (77). Overexpression of TBX3 in embryonic mouse atrial myocytes is sufficient to induce an SAN gene program (36). However, in mature cardiomyocytes, overexpression of TBX3 induces only a subset of pacemaker-specific genes, and neither ectopic pacemaker activity nor pacemaker current (Id) was observed (47). Recent studies have demonstrated that overexpression of ISL1 in either embryonic stem cells or Xenopus embryos results in upregulation of nodal-specific genes and downregulation of transcripts of working myocardium (78),

<p>| Table 1. Direct targets of ISL1 associated with sinus node dysfunction |
|--------------------------|--------------------------|--------------------------|</p>
<table>
<thead>
<tr>
<th>Gene Name</th>
<th>RNA-seq fold-change (mut vs. ctrl)</th>
<th>Peak coordinates (chr:start-end)</th>
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<tbody>
<tr>
<td>Ank2</td>
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<td>chr3:126572673–126572817</td>
</tr>
<tr>
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<td>chr5:15856663–15856807</td>
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</tr>
<tr>
<td>Flrt2</td>
<td>-2.4</td>
<td>chr12:9670239–9670383</td>
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consistent with our observations of ISL1 action with loss-of-function studies in SAN cells. However, overexpression of ISL1 resulted in partial activation of the SAN program. Together, these observations suggest that generation of a biological pacemaker might benefit from combinatorial expression of transcription factors important to SAN identity and function, including TBX3, ISL1, and TBX18 (35, 48).

Altogether, results of these studies have given mechanistic insight into distinct cell autonomous requirements for ISL1 throughout SAN development, identifying a number of key downstream targets that can account for observed defects in SAN phenotype and function. Our studies represent the first in vivo ChIP-seq studies for SAN cells, which provide a basis for further exploration of factors critical to SAN formation and function.

Methods

Transgenic mice. Isl1fl:Neo-/- knockin, floxed Isl1 (Isl1fl/fl), and Isl1 hypomorphic (Isl1fl:Neo) mouse lines were generated as described (54, 64, 79). Strategy to generate the tamoxifen-inducible Hcn4-Cre mice (Hcn4-CreERT2) will be published separately. Briefly, a targeting cassette with CreERT2 cDNA was inserted immediately before translation initiation site (ATG) of the Hcn4 gene. Isl1 compound mutant mice (Isl1nLacZ/fl:Neo) were generated by crossing Isl1fl:Neo/+ mice with Isl1nLacZ/+ mice (63). To specifically delete Isl1 in cardiomyocytes or in the SAN, we crossed cTnT-Cre mice (65) or Hcn4-CreERT2 Isl1fl/fl mutant SAN transcriptomes revealed a total of 12,441 genes expressed (RPKM ≥ 1) in SAN cells, of which 1,035 upregulated and 3,690 downregulated in Isl1 mutant SAN cells (|fold-change mutant vs. ctrl| ≥ 1.5). (C) GO functional clustering of genes down- and upregulated in Isl1 mutant, highlighting cellular processes most significantly affected in mutant SAN (top 10 not redundant categories are shown). (D) qPCR validation analysis. mRNA expression of ion channels and associated genes, and genes involved in transcription regulation, cell cycle, and signaling pathways are shown. (E) qRT-PCR validation analysis. mRNA expression of atrial myocardial specific genes. Results are shown as fold-change Isl1 mutant vs. ctrl. n = 4 per group, P < 0.05, 2-tailed t test. See also Supplemental Figure 3 and Supplemental Tables 1 and 2.
percentage of total Tomato+ SAN cells. To assess ISL1 expression during development, ISL1+ and HCN4+ cells were counted and data were expressed as percentage of total HCN4+ cells. At least 4–6 matched sections were analyzed, and 3 samples per genotype per time point were analyzed.

**RNA-seq and qPCR.** RNA-seq was performed using the pacemaker cells FACS sorted from embryos of genotype Hcn4-CreERT2 Isl1 fl/fl (mutant) and Hcn4-CreERT2 Isl1+/+ (control). Tamoxifen was given at E10.5, and samples were harvested 36 hours after induction at E12–E12.5. The presence of a Rosa-tdTomato allele allowed the embryos expressing Hcn4-CreERT2 to be visually genotyped upon tamoxifen induction. The Tomato+ SANs of Isl1 mutant and control embryos were dissected under fluorescence microscopy. The samples for the same genotype were pooled and digested with a mixture of collagenase II (1 mg/ml)/trypsin (0.1%) for 10 minutes with periodical pipetting, and clear supernatants were collected in a 15-ml tube. The digestion was repeated until SAN tissue was totally digested. The cell suspension

Figure 7. ISL1 directly regulates a number of genes required for normal pacemaker function in mice and humans. (A) ChIP-seq ISL1-binding regions were mapped relative to their nearest TSS. Annotation includes whether a peak is in the TSS (defined as from -1 kb to +100 bp), transcription termination site (TTS; defined as from -100 bp to +1 kb), exon (coding), 5’ UTR, 3’ UTR, intronic, or intergenic. (B) Top motifs enriched in the vicinity of ISL1-binding sites. (C) GO functional clustering of genes associated with ISL1 ChIP-seq peaks (top 10 not redundant categories are shown). (D) Overlay of RNA-seq and ChIP-seq results correlates ISL1 binding with gene regulation in SAN cells. Scatterplot of RNA-Seq from Figure 6A with genes upregulated or downregulated 1.5-fold in Isl1 mutant SAN cells, colored in red and green, respectively. Up- and downregulated genes demonstrating vicinal ISL1 binding in SAN cells are black. (E) Overlay of RNA-seq and ChIP-seq results revealed 228 genes as potential direct targets of ISL1 in SAN cells. (F) GO functional clustering of these genes allowed for identification of cellular functions directly regulated by ISL1 (top 10 not redundant categories are shown). See also Supplemental Figure 4, Table 1, and Supplemental Tables 1, 2, 4, and 5.
was filtered through a 40-μm filter unit (Fisher Scientific), and endothelial cells were removed by incubation with CD31 microbeads (Miltenyi Biotec). SAN cells were resuspended in 0.5 ml DMEM medium and kept on ice until sorting. Hcn4-CreERT2-expressing pacemaker cells (Tomato+) were FACS sorted (BD FACSAria, BD Biosciences) into RNAlater (QIAGEN) and stored overnight at 4°C. The following day, the samples were centrifuged. RNAlater was removed, and the cells were frozen at −80°C. After multiple rounds of cell sorting, cells from individual collections were pooled at the time of RNA extraction. RNA was prepared using the RNeasy Mini kit (QIAGEN) following the manufacturer’s instructions and were quantified using a NanoDrop ND-1000 spectrophotometer.

RNA-seq was performed as described (82). The complete RNA-seq datasets are available from the Gene Expressing Omnibus database (http://www.ncbi.nlm.nih.gov/geo/) under the accession number GSE69097. Briefly, total RNA (10 ng) was incubated with Oligo(dt) magnetic beads to isolated mRNA. RNA-seq libraries were prepared with the SMARTer CDNA library construction kit (Clontech) according to manufacturer’s instructions and sequenced using Illumina HiSeqTM 2000 with paired-end sequencing at 90-bp read length (BGII). Adapter and poor-quality reads sequences were trimmed with Trim Galore (Babraham Bioinformatics) using default settings for paired-end reads. Trimmed reads were then quality controlled with FastQC (http://www.bioinformatics.bbsrc.ac.uk/projects/fastqc). On average, each read pair resulted in approximately 22 million uniquely mapped reads after mapping to the mm9 reference genome with TopHat2 (83) and Bowtie2 (84). Transcript expression values were determined after transcript normalization (reads per kilobase per million; RPKM) with AltAnalyze (85). Transcripts were considered significantly expressed if RPKM ≥ 1 in either one of the 2 conditions. Differential expression analysis was performed considering [fold-change isl1 mutant vs. ctrl] ≥ 1.5 fold as a cut-off. For scatterplot representation, values are log2 transformed tag counts normalized to 10 million uniquely mapped tags. GO and Reactome pathway enrichment analysis was conducted with GO-Elite (http://www.genmapp.org/go_elite) (86).

qPCR validation of RNA-seq targets were performed using SAN pacemaker cells as described above. qPCR was performed using SYBR green detection. Primer pairs are listed in Supplemental Table 3. ChIP-sequencing and data analysis. For ChIP-seq assay, the SANs from Hcn4-mGFP mice at postnatal days 1–3 (P1–P3) were digested and FACS-sorted as describe above.

ChIP of ISL1 was performed with modified protocol described previously (87). The complete ChIP-seq datasets are available from the GEO database under the accession number GSE69097. Briefly, for ISL1 ChIP, 2 × 10^6 cells were first crosslinked in 2 mM disuccinimidyl glutarate (Pierce Biotechnology) in PBS for 30 minutes, then subsequently in 1% formaldehyde (Sigma-Aldrich) in PBS for 10 minutes, all at room temperature. The reactions were quenched by adding glycine (Sigma-Aldrich) to a final concentration of 125 mM. The cells were immediately centrifuged (5 minutes, 700 × g, 4°C) and washed twice with ice-cold PBS. Cells were resuspended in swelling buffer (10 mM HEPES/KOH pH7.9, 85 mM KCl, 1 mM EDTA, 0.5% IGEPA-C, 630 μM [Sigma-Aldrich], 1× protease inhibitor cocktail [Roche Applied Science], 1 mM PMSF) for 5 minutes. Cell pellets were spun down and resuspended in 1 ml RIPA buffer (10 mM Tris/HCl pH 7.6, 1 mM EDTA, 1 mM EGTA, 0.1% SDS, 0.1% Na-Deoxycholate, 1× Triton X-100, 1× protease inhibitor cocktail [Roche Applied Science], 1 mM PMSF). Chromatin was sheared to an average DNA size of 100–400 bp by administering 10 pulses of 30-second duration at 12 W power output with 60-second pause on wet ice using a Misonix 3000 sonicator. The lysate was cleared by centrifugation (5 minutes, 16,000 × g, 4°C). Supernatant (1%) was kept as ChIP input. Meanwhile, Dynabeads Protein G were prepared with the ISL1 antibody (39.4D5, DSHB) by incubating Dynabeads Protein G and 5 μg specific antibody in 0.5% BSA/PBS for 1 hour at 4°C on rotator, then washed twice with 0.5% BSA/PBS and brought up to the original volume with 0.1% BSA/PBS. The protein-DNA complex of interest was immunoprecipitated by rotating the supernatant with 30 μl Dynabeads Protein G coated with specific antibody overnight at 4°C (Invitrogen). Beads were washed with each buffer rotating in 1 ml buffer at 4°C for 5 minutes: RIPA buffer (10 mM Tris/HCl pH 7.6, 1 mM EDTA, 1 mM EGTA, 0.1% SDS, 0.1% Na-Deoxycholate, 1% Triton X-100, 1× protease inhibitor cocktail [Roche Applied Science], 1 mM PMSF), LiCl buffer (0.25 M LiCl, 1% NP40, 1% NaDOC), Tris-EDTA (TE) plus 0.2% Triton X-100, and TE plus 50 mM NaCl. Immunoprecipitated chromatin was eluted twice with 100 μl elution buffer each (TE, 2% SDS) into fresh tubes for 30 minutes and 10 minutes, respectively. Eluates were pooled, the Na+ concentration was adjusted to 300 mM with 5 M NaCl, and crosslinks were reversed overnight at 65°C in a hybridization oven. The samples were sequentially incubated at 37°C for 1 hour each with 0.33 mg/ml RNase A and 0.5 mg/ml proteinase K (Sigma-Aldrich). The DNA was isolated using the ChIP DNA Clean & Concentrator (Zymo Research Corp.) according to the manufacturer’s instructions.

Sequencing libraries were prepared from collected ISL1 ChIP and corresponding input DNA by blunting, A-tailing, adaptor ligation as previously described (88) using NEXTFlex barcoded adapters from Bio Scientific. Libraries were PCR-amplified for 12–15 cycles, size selected for 225–375 bp fragments by gel extraction, and single-end sequenced on a Hi-Seq 2500 (Illumina) for 50 cycles. Reads were aligned to the mouse mm9 genome assembly (NCBI Build 37) using Bowtie allowing up to 2 mismatches. Only tags that mapped uniquely to the genome were considered for further analysis. Genomic binding peaks for transcription factor ISL1 were identified using the findPeaks command from HOMER (http://homer.salk.edu/homer/) with 8-fold enrichment over the input sample, 4-fold enrichment over local background, a minimal tag number of 16, and normalization to 10 million mapped reads per experiment (88). Peaks were annotated using the annotatePeaks command, assigning to gene targets based on the closest RefSeq-defined transcription start site (TSS). Identification of ISL1-associated transcription factor binding motifs was carried out with command findMotifsGenome.pl using a standard background as random genomic sequence sampled according to GC content of input sequences. GO and Reactome pathway enrichment analysis was conducted with GO-Elite (86).

Echocardiography. Pregnant mice were anesthetized with isoflurane. Echocardiography was performed utilizing a VisualSonics Vevo770 high-resolution ultrasound system with a RMV704 probe (40 MHz). The position of individual embryos was scanned and identified, and a map with individual embryos was drawn. B-mode and pulse-wave Doppler images were obtained to allow for assessment of heart-rate and stroke volume. After echocardiography, embryos were dissected, correlated to the map, and genotyped for phenotype-genotype correlations.
Statistical Data. Data were presented as mean ± SEM, and a 2-tailed t test was used for 2-group comparisons. Differences were considered statistically significant at a value of P < 0.05.

Study approval. All the experiments involving mice were carried out in accordance with protocols approved by the Institutional Animal Care and Use Committee of USC (A3033-01) and by the Animal Committee of Tongji University School of Medicine (Tjmed-010-10).

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